Super B Factories

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After the establishment of the Kobayashi-Maskawa mechanism of CP violation at the two B factories, possibilities to increase the integrated luminosity by two orders of magnitude have been investigated, since it seems to be the amount needed to find physics beyond the Standard Model through CP violating and other observables in rare B meson decays, D meson decays and τ lepton decays. This report reviews the physics sensitivities and status of such super B factories, which are planned at two locations.

1. Introduction

Confirmation of CP violation in B meson decays through the measurement of the time-dependent decay rate asymmetry has demonstrated the power of the high luminosity B factories, Belle at KEKB, KEK and BaBar at PEP-II, SLAC. Together with measurements of the angles and sides of the Unitarity Triangle, the picture of CP violation through the Kobayashi-Maskawa mechanism has been established to be at least the dominant source of all CP violating phenomena in the high energy physics known to date. This was possible only by building the "B factories" with two orders of magnitude higher luminosity than existing facilities at that time, and with a new concept of the boosted center-of-mass frame with asymmetric beam energies for an e^+e^- collider. The B factories have also provided a rich field for many other non-trivial tests of the Standard Model (SM) with their power based on a huge statistics of B decays, D decays and τ decays.

However, in spite of its success, the SM is still considered to be a low energy approximation of a more fundamental physics beyond the SM (BSM) for many reasons. For example, CP violation in the SM cannot explain the baryon number asymmetry in the universe; another more theoretical argument is that BSM physics is expected to lie at the TeV energy scale in order to solve the hierarchy problem. On the other hand, there is a mystery called the flavor problem: a new interaction around a TeV energy scale would alter the flavor changing neutral current amplitudes and a large deviation due to BSM would be expected, unless the coupling constants are fine tuned or aligned to the SM couplings to reconcile with the strong constraints from B factory measurements.

BSM effects should appear in most cases through loop diagrams, while the tree diagrams are usually unaffected. To observe the effects on the Unitarity Triangle of different contributions of loop and tree diagrams, and also through other rare phenomena, it is again necessary to build a new facility with a further two orders of magnitude higher luminosity than now. This is the motivation for a "super" B factory.

2. Physics Programs

The key measurement at a super B factory will still be the measurement of the Unitarity Triangle, but with a precision an order of magnitude better than what we have now. There are also a large number of other potential measurements that are sensitive to BSM, and their importance will be more significant than has been the case in Belle and BaBar. More thorough and detailed studies can be found in [1, 2, 3, 4].

2.1. Unitarity Triangle

The current world average on the angle ϕ_1 of the Unitarity Triangle[1] has a remarkable precision, $\phi_1 = (21.1 \pm 0.9)^\circ$ [5], where the error is dominated by the results from the two B factories using the sum of the datasets exceeding 1 ab^{-1}. Measurement of this and other angles, and the sides of the Triangle were made possible only after the B factories came online. All the results so far are found to be consistent with each other. However, they are not precise enough yet to identify any possible discrepancy, for example in the CP violating phase measured in the loop diagrams in which BSM effects could reside, from the phase measured from tree diagrams in which BSM effects are not expected.

The angle ϕ_1 is measured in the form of $\sin 2\phi_1$, which is the coefficient of the sine term ($\mathcal{S}$) in the time-dependent CP asymmetry that appears due to an irreducible complex phase in the $B^0\overline{B}^0$ mixing when measured together with the $b \to c\bar{c}s$ transition into a CP eigenstate such as $J/\psi K^0_S$. At this moment the measurement of $\sin 2\phi_1$ is still slightly statistical error dominated. An early dataset of 5 ab^{-1} from a super B factory will turn this into an ultimate measurement of $\sin 2\phi_1$ with an error of 0.015 (or 0.6° in terms of ϕ_1). The precision of the measurement then matches the theoretical uncertainty, which appears due to the

[1] In this report, the notation ϕ_1, ϕ_2, ϕ_3 is used instead of β, α and γ.

effects of subdominant diagrams with the same final state, a complex phase different from ϕ_1 and an unknown size of the amplitude.

The angle ϕ_2 appears in the combination of the $B^0\overline{B}^0$ mixing and the $b \to u$ transition into a CP eigenstate such as $B \to \pi^+\pi^-$. Unfortunately, $\sin 2\phi_2$ cannot be directly measured from the time-dependent asymmetry of $B \to \pi^+\pi^-$ due to the $b \to d$ penguin contribution which has a different weak phase. The amplitude of such a contribution and the angle ϕ_2 have to be extracted from measurements of all $\pi\pi$ charge combinations ($\pi^+\pi^-$, $\pi^\pm\pi^0$, $\pi^0\pi^0$) by assuming isospin symmetry. The same is possible with $B \to \rho\rho$, or a more elaborate technique can be performed to disentangle the amplitudes and phases of $B \to \rho\pi$ using a time-dependent Dalitz analysis of $B \to \pi^+\pi^-\pi^0$. Multiple solutions appear in these procedures and they make it difficult to pinpoint the value of ϕ_2; the current 1σ interval from combined Belle and BaBar results is $[83.5, 94.0]^\circ$, e.g., in [6]. A super B factory will significantly improve the situation as the correct solution will become unambiguous from the three independent measurements. The combined error for ϕ_2 is about 2° with 5 ab^{-1} data. This is the ultimate precision at which the experimental error matches the model uncertainty of the Dalitz amplitudes or theoretical uncertainty due to isospin breaking effects.

At a super B factory, the set of angles ϕ_1 and ϕ_2, already with 5 ab^{-1}, provides a reference "point" of the Unitarity Triangle with a 2% error. All of the other possible measurements will be used to search for a deviation of $O(10\%)$ from the SM.

2.2. Deviation from the Unitarity Triangle

The three most promising measurements to search for a deviation from expectation for the Unitarity Triangle variables are; the angle ϕ_1 from loop mediated $b \to s$ decays, the angle ϕ_3 from the tree process $B \to D^0K$, and the length of the side $|V_{ub}|$ using $b \to u\ell\nu$ decays. Any deviation from the reference point defined by (ϕ_1, ϕ_2) becomes evidence of BSM.

In the SM, the size of the time dependent CP asymmetry $\mathcal{S}$ in the $b \to s\overline{q}q$ decay modes into a CP eigenstate is the same as that in $b \to c\overline{c}s$, i.e. $\sin 2\phi_1$, as both diagrams have the same weak phase. Since $b \to s\overline{q}q$ is a penguin loop, the phase can be modified by an additional BSM amplitude if it exists, while it is unchanged in $b \to c\overline{c}s$. Therefore, the deviation in $\mathcal{S}$ from $\sin 2\phi_1$ is the sign of BSM. For a given final state, there are always subdominant diagrams, e.g., the tree diagram $b \to u$ with $s\overline{u}$, which are the source of possible modification of $\mathcal{S}$ within the SM. Three modes, $B \to \phi K^0$, $B \to \eta' K^0$ and $B \to K^0_S K^0_S K^0_S$, are considered to be the golden modes with the smallest of such pollutions, estimated to be about 0.02. Measurements will be statistical error dominated until 50 ab^{-1} or more integrated luminosity is obtained, as shown in Fig. 1. The expected errors are, 0.02, 0.03 and 0.04 for $B \to \eta' K^0$, $B \to \phi K^0$ and $B \to K^0_S K^0_S K^0_S$, respectively, at 50 ab^{-1}.

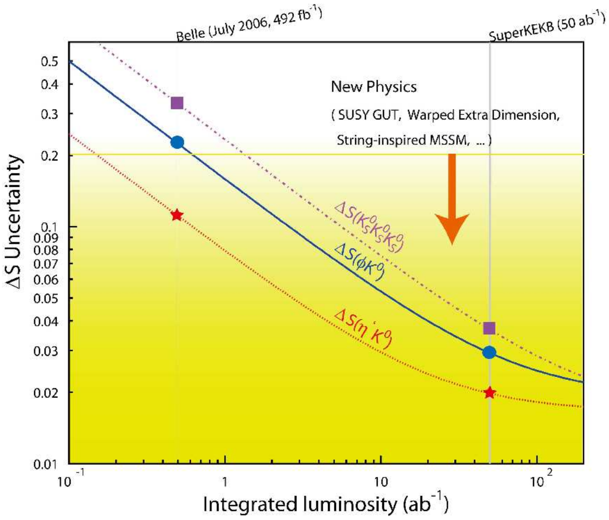

Figure 1: Expected sensitivities of the CP violation measurements in $B \to \eta' K^0$, $B \to \phi K^0$ and $B \to K^0_S K^0_S K^0_S$ decays as a function of the integrated luminosity at SuperKEKB.

The angle ϕ_3 is most cleanly measured using $B \to D^0K$ decays. There, ϕ_3 appears as interference between the tree amplitude $b \to c$ with $d\overline{u}$ and another tree amplitude $b \to u$ with $d\overline{c}$. The former gives $\overline{D}^0$ in the final state while the latter gives D^0; common final states between D^0 and $\overline{D}^0$ decays are the source of interference between these two decay channels. As there is no subdominant amplitude with a loop diagram, this provides the cleanest SM measurement. There are several methods depending on different D^0 decay modes, e.g., D^0 decaying into a CP eigenstate, or into a doubly Cabibbo suppressed final state. The most effective method is based on the Dalitz analysis of the decay chain $B^\pm \to DK^\pm$; $D \to K^0_S\pi^+\pi^-$. The analysis depends on the model of the three-body D decay amplitudes, and gains significantly from charm factory data with CP-tagged D^0 decays. The combined ϕ_3 error will be 6° at 5 ab^{-1}, or 2° at 50 ab^{-1}.

The $|V_{ub}|$ measurement is performed using either an inclusive measurement of $B \to X_u\ell\nu$ or an exclusive one such as $B \to \pi\ell\nu$. Currently, both measurements have a similar size in the error, and have some tension between the results. Both methods provide the cleanest results using a tagging technique of reconstructing a hadronic B decay mode for the other B meson decay. The tagging efficiency is not very high and demands huge statistics which is suitable at a super B factory. Since only a limited kinematical range can be measured due to the huge $b \to c\ell\nu$ background, the inclusive measurement requires the operator prod-

uct expansion technique to extrapolate into the full kinematical range. All the necessary information is available from data, and the total error will be 6% at 5 ab^{-1} and 4% at 50 ab^{-1}. The exclusive branching fraction will be more accurately measured at a super B factory. If the $B \to \pi$ form factor is calculated using lattice QCD more precisely, $|V_{ub}|$ will be determined from the exclusive measurement with a smaller error.

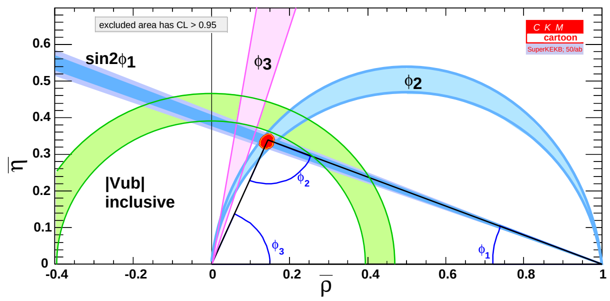

Figure 2: Expected sensitivities of the Unitarity Triangle measurements at 50 ab^{-1} data at SuperKEKB.

Expected sensitivities of the Unitarity Triangle measurements at 50 ab^{-1} data at SuperKEKB is shown in Fig. 2 using the current world average values for the central values. Given these measurements, a 10% deviation in any of these measurement would be identified at a super B factory with 50 ab^{-1}.

2.3. More Key Measurements

There are many other key measurements which can be used to search for BSM in B decays, and also in decays of D mesons and τ leptons, which are equally abundantly produced at a super B factory.

The weak interaction which governs b quark decays is based on a left-handed current in the limit of massless quarks. This is not necessarily the case in many BSM models. The right-handed current in the $b \to s$ transition can be effectively identified as a non-zero $\mathcal{S}$ value in a time-dependent CP measurement of $B \to K^0_S \pi^0 \gamma$. With 50 ab^{-1} the error will be less than 3% and already better than the theoretical uncertainty on the deviation of $\mathcal{S}$ from zero due to the finite mass of the s quark.

Many BSM models also require more than one Higgs doublet, including a charged Higgs boson. The charged Higgs boson can replace the weak boson in a tree diagram, and its effect is enhanced in the helicity suppressed purely leptonic decays and semi-leptonic decays with a τ lepton. The effect can be searched for through a deviation from expectation in the branching fraction of $B \to \tau\nu$. Similar measurements can be performed with $B \to D^{(*)}\tau\nu$ and $B \to \mu\nu$. If deviations are observed in all these modes, a comparison between them leads to a test of the universality of the coupling, and provides stronger evidence for the existence of the charged Higgs boson.

Inclusive measurements such as $B \to X_s\gamma$, $B \to X_d\gamma$ and $B \to X_s\ell^+\ell^-$ are also sensitive to a wide range of BSM. Especially, the zero-crossing point of the forward-backward asymmetry in $B \to X_s\ell^+\ell^-$ has a very clean signature.

The recently observed large values of the $D^0\overline{D}^0$ mixing parameters (x, y), of the order 10^{-2}, suggest the possibility of a BSM contribution, while an explanation within the SM is not excluded because of a large hadronic uncertainty. A measurement of CP violation in $D^0\overline{D}^0$ mixing would be clear evidence for a BSM effect in the charm quark sector.

Finally, lepton flavor violating τ decay is also allowed in many BSM models, while it is not allowed at all in the SM. There are a large number of possible lepton flavor violating decay modes (e.g., $\tau \to \mu\gamma$, $\tau \to \mu\eta$ or $\tau \to e^+e^-e^+$) which have been and will be searched for. If observed, it will be an unambiguous sign of new physics.

2.4. Comparison with LHCb

There may be a question why we have to build a super B factory while the next generation flavor physics can be studied at LHCb. In reality, it is almost impossible to measure modes with photons, π^0 and neutrinos, and perform inclusive measurements at LHCb. Many of these are the key measurements to study BSM as already discussed.

There are examples where LHCb has an excellent sensitivity: the Unitarity Triangle parameters, especially the angle ϕ_3, can be precisely measured at LHCb with a similar precision to that of at a super B factory, provided that the systematic errors are under control. In order to search for a BSM CP phase in the $b \to s$ transition, $B_s \to \phi\phi$ can be used; in order to search for the right-handed current, $B_s \to \phi\gamma$ can be used. These are different decay modes related to searches for the same type of BSM effects, and the searches at the two places are extremely helpful for gaining an unambiguous understanding of BSM physics.

3. Next Generation B Factories

In order to collect an integrated luminosity of 50 ab^{-1} within a reasonable amount of running time, the instantaneous luminosity has to be above or at least close to $10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In addition, to keep synergy with energy frontier physics at the LHC and flavor physics at LHCb, it is crucial to operate the super B factory in the next decade.

Currently, two projects are planned: the SuperKEKB project in Japan and the SuperB project in Italy. If resources allow, it is definitely better to

have both facilities for healthy competition and cross-checks, as was extremely helpful in the case of competition between Belle and BaBar. However, under the current situation for high energy physics, it does not seem to be possible to have both of them at the same time.

Key parameters for a high luminosity are the beam current (I) and the beam-beam parameter (ξ_y) that are proportional to the instantaneous luminosity, and the vertical β function at the interaction point (β_y^*) which is inversely proportional to the luminosity. The two projects take different approaches for a higher luminosity. Typical parameters for SuperKEKB are beam currents of 9.4 A $\times$ 4.1 A, $\xi_y > 0.24$ and $\beta_y =$ 3.0 mm for both rings. Those for SuperB are 1.85 A $\times$ 1.85 A beam currents, $\xi_y = 0.15$ and $\beta_y = 0.39/0.22$ mm for the high/low energy ring. An example of the parameters is given in Table I. These parameters give instantaneous luminosities of $0.8 \times 10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for SuperKEKB and $1.0 \times 10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for SuperB, almost two orders of magnitude higher than the current KEKB record, $0.017 \times 10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Table I An Example of machine parameters for SuperKEKB and SuperB.

	SuperKEKB		SuperB	
	(e^+)	(e^-)	(e^+)	(e^-)
Energy (GeV)	3.5	8	4	7
Luminosity (10^{36})	0.55		1.0	
Number of bunches	5018		1251	
Beam current (A)	9.4	4.1	1.85	1.85
$\beta(y^*)$ (mm)	3		0.22	0.39
$\beta(x^*)$ (mm)	200		35	20
emittance $\epsilon(y)$ (pm.rad)	60	66	7	4
emittance $\epsilon(x)$ (nm.rad)	12	13	2.8	1.6
beam-size $\sigma(x^*)$ (μm)	37.5	39.8	0.039	0.039
beam-size $\sigma(y^*)$ (μm)	2.11	2.28	9.9	5.66
bunch length	3			
Damping time (ms)	84/–	47/–	40/20	40/20
Touschek lifetime (min)			20	40
Beam lifetime (min)			5.0	5.7
tune-shift $\xi(y)$	0.296		0.15	
tune-shift $\xi(x)$	0.153		0.0043	0.0025
RF power (MW)			17	

3.1. SuperKEKB

The SuperKEKB project is an upgrade of the current KEKB facility at the same place, reusing a large fraction of the existing components and infrastructure.

One of the key components of SuperKEKB is the "crab" cavity that rotates the envelope of the beam bunch and makes head-on collisions possible for beams incident at a finite angle (crab-crossing). This will at least geometrically increase the effective volume of the collision. According to a simulation, the effect is more dramatic: the beam-beam force becomes nearly independent of the horizontal coordinate at a half integer tune. In the case of KEKB with a 22 mrad crossing angle, ξ_y becomes 0.15 and almost doubles the luminosity, and for SuperKEKB with a 30 mrad crossing angle, $\xi_y > 0.24$ is possible.

With this simulation result, KEKB has installed a crab cavity for each of high and low energy rings and has been commissioning since 2007. Under a low beam current operation, the specific luminosity reached the predicted value (Fig. 3), and an enhancement in the beam-beam parameter, $\xi_y = 0.092$, with respect to the case before the crab cavity, $\xi_y = 0.056$, was observed. However, there is a drop in the luminosity under a high beam current, and the reason is still being investigated. In addition, the current crab cavity has to be operated at a lower beam current than what was already achieved without, and this has prevented the expected boost in the instantaneous luminosity so far. The commissioning will continue for one more year until the end of the KEKB running time.

The other key issue is the higher beam current. In order to store a higher beam current without being affected by the electron cloud, the vacuum pipe will be replaced all over the ring with antechamber type beampipes, and the bellows with higher-current-proof ones.

The KEKB upgrade plan is already included in KEK's five-year roadmap from 2009 to 2013. This includes a three-year shutdown time for the construction.

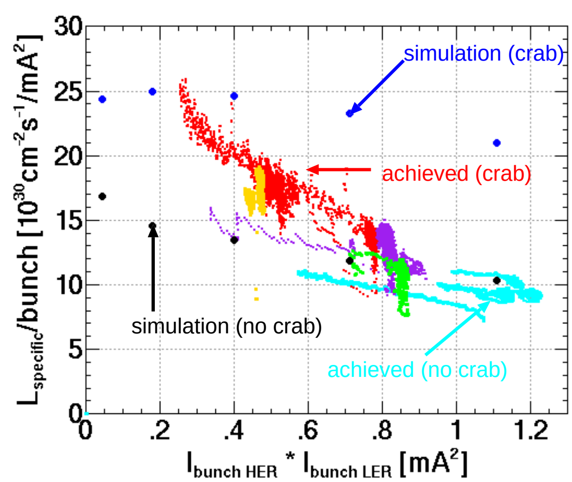

Figure 3: Specific luminosity simulated and measured with and without the crab cavity at KEKB.

3.2. Italian SuperB

The SuperB project in Italy is a completely new project, with an ultra low emittance approach inspired by the International Linear Collider (ILC) project. In order to achieve a very high luminosity with a moderate beam current, both beams have to be squeezed into an extremely small interaction region with a vertical size of 39 nm, and with a very small β_y^*. Such a beam could be possible, according to the studies for the ILC dumping ring. However, it does not necessary mean that such a small emittance can be sustained while making collisions at every turn with a very high luminosity. The other problem would be the very short beam lifetime of about only five minutes.

The ultra-small beamsize also implies a huge hourglass effect, and it has to be suppressed either by making the bunch length extremely short, which is not realistic, or by moving the vertical waist positions of both beams along the z axis with a proper phase. The latter is called the "crab waist", and can be realized with a sextupole magnet. The concept of the crab waist has been successfully tested at DAΦNE at a low energy and low beam current, as shown in Fig. 4.

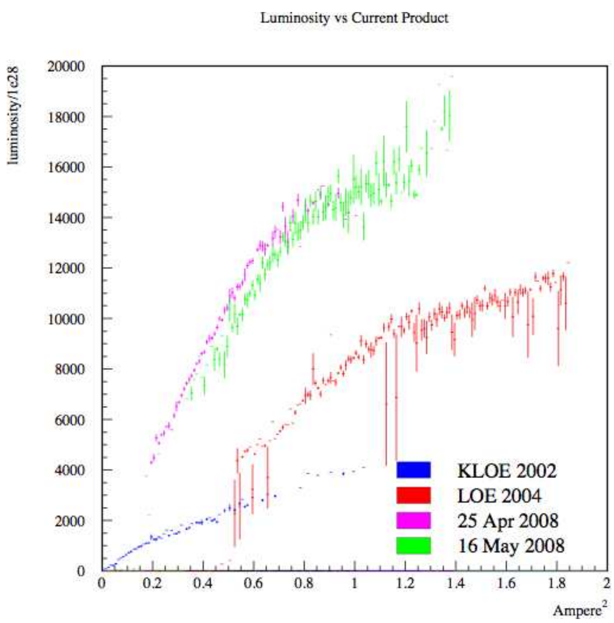

Figure 4: Luminosity improvement with the crab waist scheme measured at DAΦNE.

The other consideration at SuperB is to make the energy asymmetry smaller, in order to save on the electricity bill. This makes the resolution of the time difference between two B meson vertices worse, but it gives a better hermeticity, which is crucial for measurements with neutrinos.

The candidate site is at the Tor Vegarta campus of INFN Rome. Here also, many components, including magnets, will be brought from PEP-II to minimize the cost.

4. Detector Considerations

A high luminosity brings a high event rate. The B-pair events alone will be delivered at a rate of 1 kHz under a luminosity of $1 \times 10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and the physics trigger rate will become 10 kHz excluding the Bhabha events, which have an even higher rate. In order to keep nearly 100% efficiency for the B-pair events, the trigger and data acquisition system have to be drastically improved. The readout electronics also has to be as deadtime-free as possible.

A high luminosity brings a high background rate at the same time. On the other hand, to keep the advantage of the clean e^+e^- environment especially for measurements with photons, π^0 and neutrinos, any performance drop with respect to the current Belle or BaBar detector is not acceptable.

Since the existing Belle and BaBar detectors already have excellent performance, it is not easy to drastically improve it, especially after coping with the high background.

4.1. SuperKEKB Detector

The detector at SuperKEKB (SuperBelle) has to cope with the large beam-gas background due to the much higher beam currents. After a careful design of the beampipe and masks at the interaction region, it is found that the size of Touschek background is moderate, and the radiative-Bhabha background is not harmful except for the outmost K_L and muon detector. The total background will be about 20 times that of the current conditions at Belle, and therefore a significant amount of modification to the Belle detector is necessary.

In order to cope with the background, the following changes are planned. The silicon vertex detector will have a larger radius with six layers, with a possible option of a pixel detector for the innermost layer. The enlarged vertex detector will replace the inner part of the drift chamber and allow a larger volume for $K_S^0 \to \pi^+\pi^-$ vertexing. The drift chamber will be replaced with one with smaller cell size to shorten the drift time and to reduce the occupancy. The outer radius of the drift chamber will be enlarged, thanks to the thinner outer detectors. The particle identification devices will be fully replaced from existing time-of-flight counters and the threshold-type aerogel Cherenkov counter, with a detector to reconstruct the Cherenkov ring image, such as a time-of-propagation counter for the barrel part and an aerogel ring-image counter for the forward endcap part. The endcap part of the calorimeter will be replaced with pure CsI

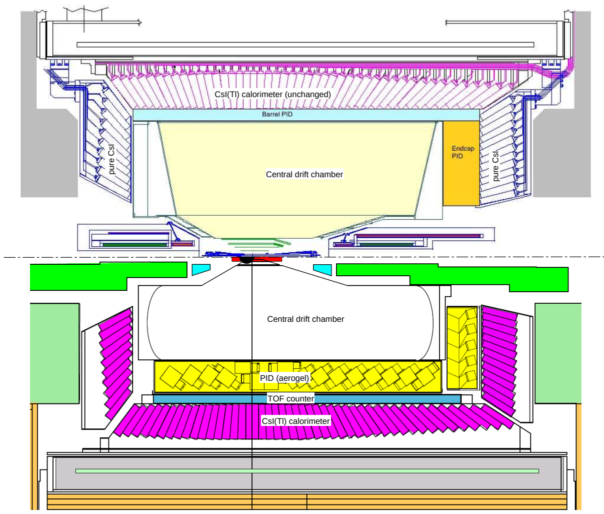

Figure 5: Comparison between the SuperBelle detector (upper) and the Belle detector (lower).

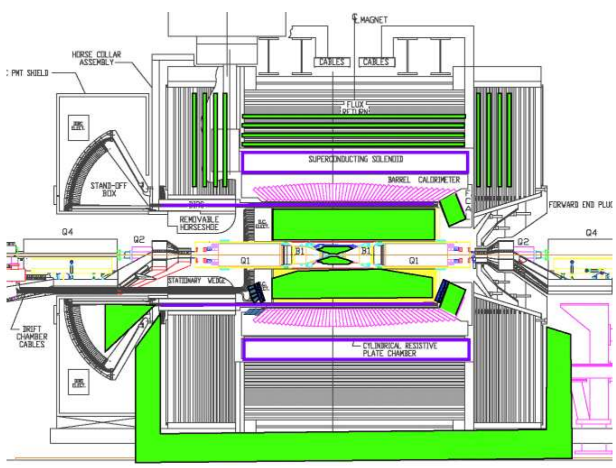

Figure 6: SuperB detector without (upper) and with (lower) optional detector components.

crystals that have a faster time response, while the thallium-doped CsI crystals will be unchanged for the barrel part. The resistive plate counters for K_L^0 and muon detection will be replaced with scintillation fibres.

4.2. SuperB Detector

Thanks to the smaller beam current, the beam-gas background is expected to be moderate at the SuperB detector. On the other hand, a huge Touschek background is expected, and also the very short lifetime could be harmful for the detector.

The detector is based on reuse of the existing BaBar detector, which is already more immune to backgrounds than Belle. However, similarly to Belle's case, many of the components have to be replaced. These includes a new silicon vertex tracker, a new drift chamber, a new forward calorimeter and a new K_L^0 and muon detection system.

5. Summary

The physics program at a super B factory is very compelling in the integrated luminosity range between 5 to 50 ab^{-1}. This includes the measurements of the precise reference point in the Unitarity Triangle and possible deviations from there, extensive searches for right handed currents, charged Higgs, lepton-flavor violating decays, and many other search channels.

Both projects described in this paper are actively working on the accelerator and detector designs. The design for SuperKEKB is already finalizing for the production of necessary components, while the SuperB design is also getting converged. We are looking forward to the exciting future of flavor physics that will be possible at a super B factory.

References

[1] A. G. Akeroyd *et al.*, arXiv:hep-ex/0406071.
[2] M. Bona *et al.*, arXiv:0709.0451 [hep-ex].
[3] T. Browder *et al.*, arXiv:0802.3201 [hep-ph].
[4] M. Artuso *et al.*, arXiv:0801.1833 [hep-ph].
[5] HFAG group, E. Barberio *et al.*, arXiv:0808.1297 [hep-ex] and online update at http://www.slac.stanford.edu/xorg/hfag.
[6] CKMfitter Group, J. Charles *et al.*, Eur. Phys. J. **C41**, 1-131 (2005), and online update at http://ckmfitter.in2p3.fr.